Speckle noise in a continuously scanning multi-beam laser Doppler vibrometer for acoustic landmine detection

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ABSTRACT

The multi-beam laser Doppler vibrometer (MB-LDV) has been successfully used for acoustic landmine detection in field experiments at an Army test site. Using the MB-LDV in a continuously scanning mode significantly reduces the time of the measurement. However, continuous motion of a laser beam across the ground surface generates noise at the vibrometer output due to dynamic speckles. This speckle noise defines the noise floor and detectability of the system. This paper studies the origins of speckle noise for a continuously scanning LDV. The structure of the speckle field exhibits points of phase singularity that normally coincide with signal dropouts. The signal dropouts and phase singularities can cause spikes in the demodulated velocity signal, which increase the noise in the velocity signal. The response of FM demodulators to input signals causing spikes in the LDV output are investigated in this paper. Methods of spike reduction in the LDV signals have been developed and experimentally investigated. This research is supported by the U. S. Army Research, Development, and Engineering Command, Communications-Electronics Research, Development, and Engineering Center, Night Vision and Electronic Sensors Directorate.

Keywords: land mine detection, laser-acoustic sensing, laser Doppler vibrometer, LDV

INTRODUCTION

Acoustic landmine detection using a continuously scanning multi-beam laser Doppler vibrometer (MB-LDV) as a vibration sensor has demonstrated promising results in laboratory and field experiments[1,2]. A generic schematic of the method is presented in Figure 1. The technique uses airborne sound or mechanical shakers to excite vibration in the ground and a continuously scanning MB-LDV is then used to measure the ground vibration at multiple points. The presence of a buried landmine can be detected by studying the spatial distribution of the ground velocity spectra. A schematic of the MB-LDV and its principles of operation were described in detail in references[3,4]. The principle of measurement is based on detection of the Doppler shift of laser light scattered from a vibrating object. The MB-LDV is a multi-channel laser heterodyne interferometer. The laser beam is split into 16 object beams and 16 reference beams. The reference beams are frequency shifted by 100 kHz. The 16 object beams are focused onto a target along a line. The light backscattered from the target is optically mixed with the reference beams, producing 16 frequency modulated signals having a 100 kHz carrier frequency. The frequency deviation (Doppler shift) of each signal is proportional to the velocity of the target at the point of measurement. The output signals of the multi-beam LDV, after demodulation by an FM demodulator, are proportional to the velocity of the target. The target velocity spectrum of each beam is then calculated in software.

Use of the multi-beam LDV developed by MetroLaser in a continuously scanning mode significantly reduces the time of the measurements. The MB-LDV illuminates the ground with a linear array of 16 beams spread along a one meter line, and measures the ground velocity at all 16 points simultaneously while the 16 beams move in the transverse direction across the interrogated area. A two-dimensional velocity map of the ground over one square meter can thus be obtained in a time less then 20 seconds.

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A continuously scanning beam introduces additional noise to the measurements due to dynamic speckles, which increase the velocity noise floor of the vibrometer. It was shown earlier[2] that the velocity noise increases due to phase fluctuation of dynamic speckles and due to spikes in the frequency demodulated signal. Spikes in FM demodulators are caused by input noise when the input signal-to-noise ratio is low and the amplitude of the noise becomes comparable in magnitude to the amplitude of the carrier signal. It will be shown below that another origin of spikes in the signal of a scanning LDV is associated with wavefront dislocations, or optical vortices, in the speckle fields. The noise energy associated with spikes is very large compared with the energy of thermal noise. Therefore, removing the spikes from the demodulated LDV signals will decrease the noise floor of the vibrometer and improve the detectability of the landmine detection system. In this paper we have studied the origins of spikes in continuously scanning LDV signals and developed methods to detect spikes and remove them from LDV signals. The "de-spiking" technique was applied to field data taken with the continuously scanning MB-LDV at an Army eastern temperate site.

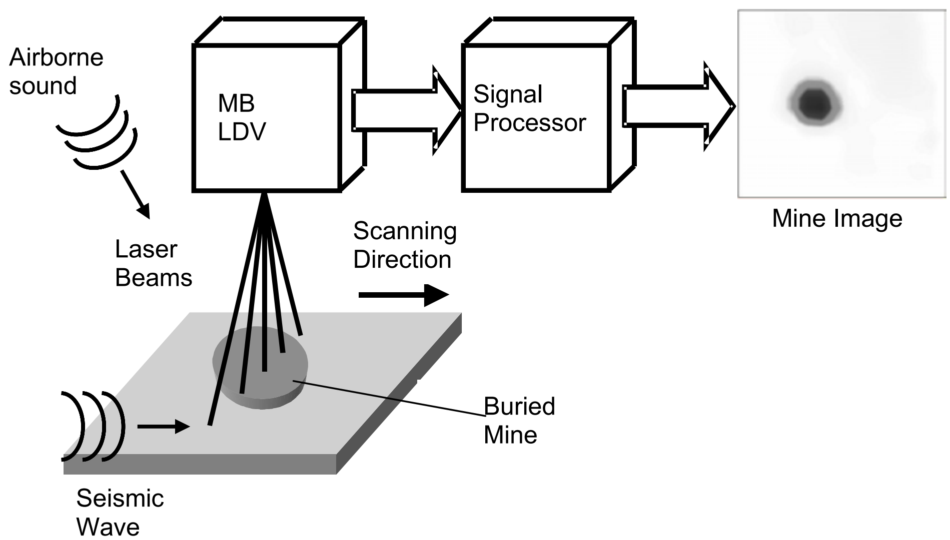

Figure 1. Schematic illustrating the use of scanning MB-LDV for acoustic landmine detection

2. SPIKE ORIGINS IN A CONTINUOUSLY SCANNING LDV SIGNALS

When a laser beam moves across a target, the intensity and phase of the speckles change in a random way. This results in random fluctuations of the amplitude and phase of the Doppler signal. The Doppler signal at the output of a photodetector can be written as:

$$i_d = kJ\cos\left[2\pi\left(f_R + f_D\right)t + \left(\Phi_R - \Phi_S\right)\right] \tag{1}$$

where $J = 2k\left(P_R P_S\right)^{1/2}$ is the amplitude of the Doppler signal, k is the sensitivity of the photodetector, P_R and P_S are the optical power of the reference beam and the scattered object light at the photodetector respectively, Φ_R and Φ_S are the phase of the reference light and the scattered object light respectively, and f_R and f_D are the frequency shift of the reference radiation and the Doppler shift of the object radiation respectively. Since the Doppler signal results from coherent addition of the reference beam and the speckle field, the amplitude J and the phase $\Phi = \Phi_R - \Phi_S$ of the Doppler signal are random quantities. The amplitude of the Doppler signal can occasionally

drop down to a low level and the amplitude of noise becomes comparable in magnitude to the carrier amplitude. In that case spikes can appear in the output of the FM demodulator because the phase of the sum of the carrier signal and noise is likely to change by 2π in a relatively short time, since the noise varies much faster than the modulating signal. This rapid change of phase by 2π results in a sharp spike in the frequency demodulated signal. The spike noise has a broadband energy spectrum, so, the noise caused by spikes can not be reduced by a baseband filter at the output[5].
The random phase fluctuation of the speckles results in random fluctuation of the Doppler frequency and contributes to the velocity noise floor of an LDV. The frequency f_C of the carrier signal of the LDV is given by the time derivative of the cosine function in the expression (1):

$$f_C = f_R + f_D + \frac{1}{2\pi}\frac{d\Phi_S(t)}{dt}. \tag{2}$$

When the laser beam is stationary and the target exhibits only out-of-plane vibration, the speckles on the photodetector do not change with time and $d\Phi_S/dt = 0$, making the frequency of the carrier Doppler signal equal to $f_C = f_R + f_D$.

When the speckles move due to the beam moving across the target, the phase variation $d\Phi_S/dt$ is proportional to the phase gradient of the speckle field and the speed of the scanning laser beam. The noise corresponding to the frequency content of $d\Phi_S/dt$ appears in the signal. As a result these fluctuations produce random noise at the vibrometer output for a continuously scanning beam. The phase gradient is different for different areas of the speckle field. The average speckle gradient of the whole speckle field is 172 degrees per coherence length of the speckle field[6]. The phase gradient is around 49 degrees per coherence length at the center of a speckle spot while it can exceed 3500 degree per coherence length at non-zero amplitude minima.

A speckle field contains wavefront screw dislocations, or optical vortices, in which the surface of constant phase has a helicoidal form[7]. The amplitude of the electric field and the intensity of the speckle field becomes zero at the dislocation center. The closed path around the point of singularity causes the change in phase by 2π. Depending on the sign of the phase shift, +2π or –2π, in tracing around the point of singularity, dislocations can be positive or negative. The phase changes discontinuously by +π or –π, depending on the sign of dislocation, along every line that passes through the center of the vortex. It was shown experimentally[6] that the phase map of a speckle field consists almost exclusively of phase singularities around which the phase changes very much more rapidly than on average, and phase saddles near which the phase changes relatively slowly. Work[6] shows that the amplitude of speckles and the phase gradient are perfectly anti-correlated at phase singularities, i.e. the phase singularities normally coincide with dark speckles, or signal dropouts in the Doppler signal.

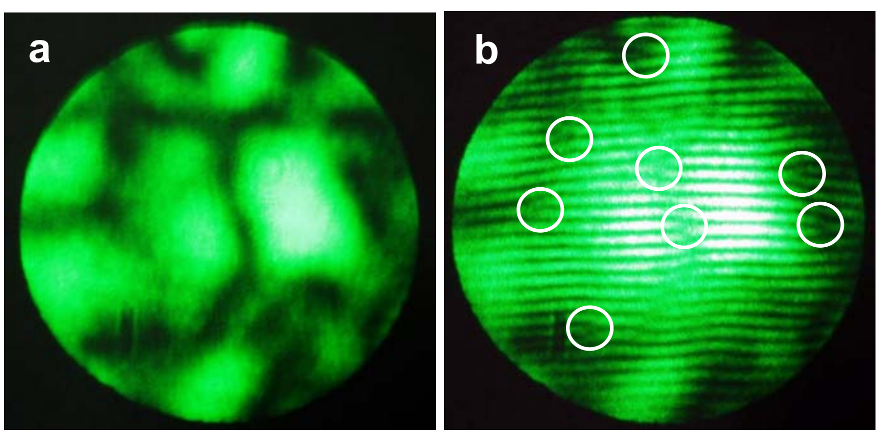

Figure 2. (a) speckle pattern, (b) interferogram of the same speckle pattern. Circles indicate wavefront dislocations.

Since the phase of a speckle field at the point of wavefront dislocations exhibits a discontinuity, a spike in the Doppler signal can occur when an area of the speckle field containing a dislocation passes in front of the LDV photodetector.

Figure 2 shows an example of optical vortices in a speckle field. Figure 2(a) shows a speckle pattern, and Figure 2(b) shows the interference of the same speckle pattern with a tilted plane reference wave. The bending of the interference fringes corresponds to the smooth variation of the phase of the speckle field or to the curvature of the wavefront. The termination or origination of a new fringe, shown with a circle, corresponds to wavefront dislocations, respectively positive or negative. When a laser beam moves across a target, the speckle pattern on the LDV photodetector moves and changes in structure. If an area of the speckle field containing a wavefront dislocation passes in front of the photodetector, the phase of the Doppler signal changes discontinuously by $+\pi$ or $-\pi$ depending on the sign of the dislocation. These phase discontinuities result in spikes in the velocity signal, because the velocity is proportional to the derivative of the phase

This phenomenom is confirmed by a simple experiment, the schematic of which is shown in Figure 3. A beam of a single beam LDV was continuously scanning a rough surface object. The output carrier signal was demodulated in amplitude, phase and frequency by using a vector signal analyzer (HP 89410A) in the demodulation mode. The speed of the beam on the target was 1.2 mm/s. One can see from Figure 4 that the phase of the signal exhibits discontinuities and they coincide with low amplitude of the Doppler signal and the corresponding intensity of speckles. The phase discontinuities result in spikes in the frequency demodulated signal. The laser beam was scanning the same area of the target along the same trajectory. All three signals repeated themselves consistently (the location and sign of phase discontinuities in the PM demodulated signal and spikes in the FM demodulated signal did not change from scan to scan), which means they are caused mainly by the phase discontinuities of speckles, not only by noise at the demodulator inputs. The speckle field dislocation density is on the order of the number of speckles per unit area[8]. So, the number of spikes caused by phase singularities of the speckle field can be on the order of the number of speckles passing in the front of the LDV photodetector during beam scanning.

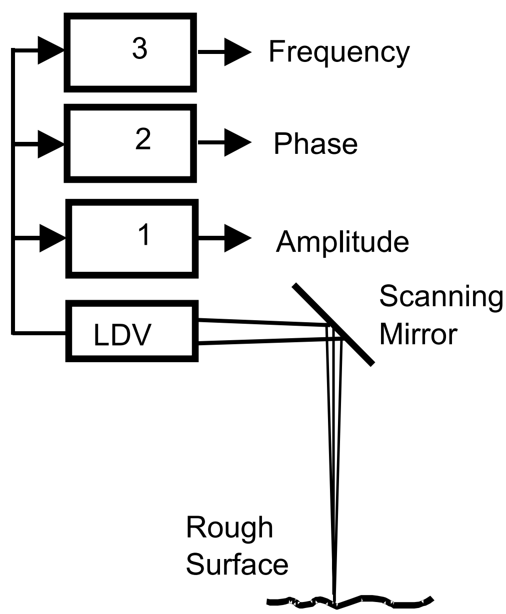

Figure 3. Layout of the experimental setup for obtaining amplitude, phase and frequency data of speckles in the scanning LDV. 1 -amplitude demodulator, 2 – phase demodulator, 3-frequency demodulator.

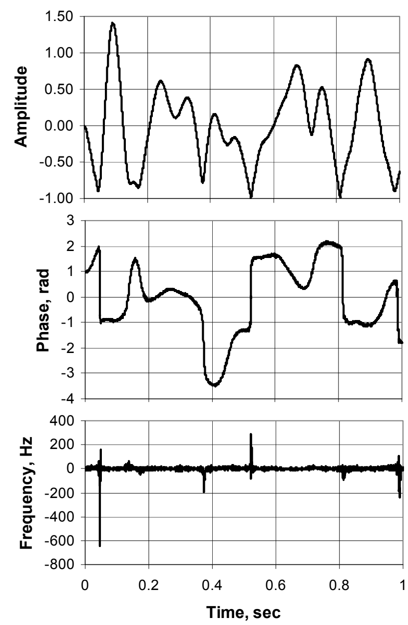

Figure 4. Amplitude, phase and frequency demodulated signal of a continuously scanning LDV.

So, spikes in the LDV signal are caused by two effects: input noise when the SNR is low and phase singularities of speckles. Figure 5 shows how these two effects influence the shape of spikes. When the SNR is high the effect of phase discontinuities dominates and a spike is a narrow unidirectional impulse-Figure 5 (a). When the SNR decreases the spikes become noisier and wider bursts of noise – Figure 5 (b - d).

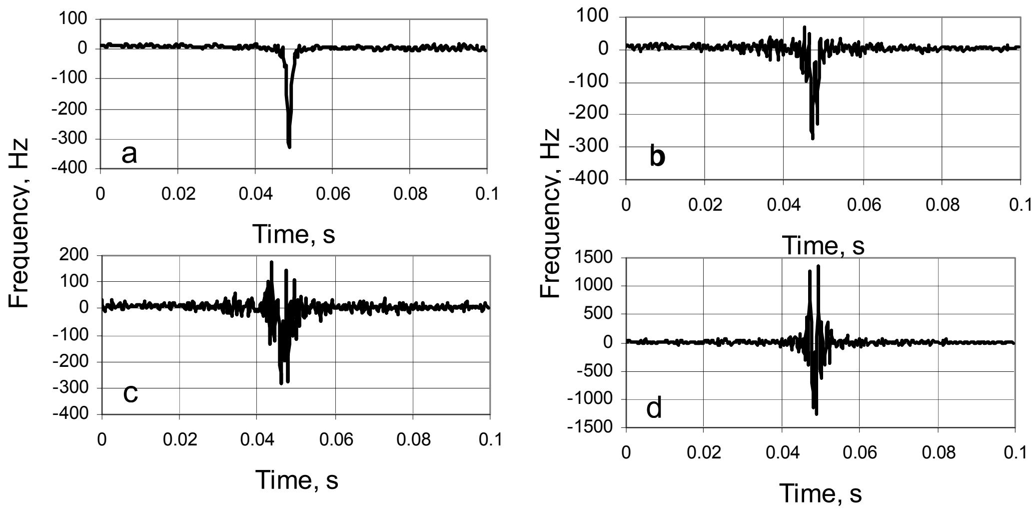

Figure 5. Spikes in the demodulated output of a continuously scanning LDV. (a) average SNR = 51dB, the spike is caused mostly by phase discontinuity of speckles, (b) average SNR = 35dB, (c) average SNR = 30dB, (d) average SNR = 21dB, (a) – (d) - the spikes are caused by the combined effect of phase discontinuity of speckles and input noise.

These results show that the shape and duration of a spike will depend on the threshold of the FM demodulator used. An FM demodulator with a lower threshold will produce a shorter and less noisier spike. Figure 6 shows the response of different FM demodulators: PLL, baseband I&Q, and digital direct carrier sampling (IF) to the input signals causing spikes in the output. The baseband I&Q and IF demodulators have the threshold of 10 dB lower than PLL. As a result the PLL output is noisier (Figure 6 a) compared to the spikes in the baseband I&Q and IF signals (Figure 6 b, c).

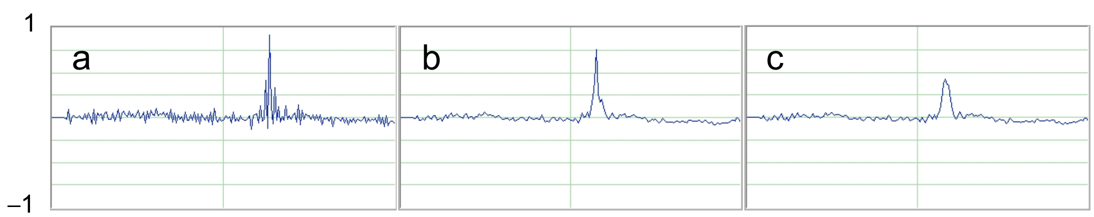

Figure 6. A spike at the output of (a) PLL demodulator, (b) baseband I&Q demodulator, (c) IF demodulator

3. METHODS OF SPIKES DETECTION AND REMOVAL

To reduce the velocity noise floor caused by spikes several methods have been developed. In the non-linear "spike-removal" filter the spike detection is based on the peak detection in the velocity signal by using high-pass filtering of the signal and subtraction of a smoothed copy of the signal. Then the segment of the signal containing a spike is replaced with the straight line or a fitted curve.

The basic steps in the spike removal algorithm are:

1. Smooth original waveform to mostly suppress the spike and preserve the signal.
2. High-pass filter the original by subtracting the smoothed version.

3. Rectify (set positive) all portions of the residual spike bursts.
4. Smooth the rectified glitches to create "bumps" (different time constant).
5. For "bump" regions above a threshold, create a binary gate.
6. Find the points just outside of the gates in the smoothed original waveform.
7. Create a straight line interpolation between these (smoothed) end-points.
8. Use the straight-line or fitted curve segment to replace this portion of original waveform.

Figure 7 shows an example of application of the described algorithm to the data set taken with the direct carrier sampling digital FM demodulator. The target velocity was 48 microns/s, vibration frequency 100 Hz, and a beam speed was 4 cm/sec. The reduction of the spikes causes the noise floor to be reduced across the entire frequency spectrum. The SNR was improved by 11.6 dB.

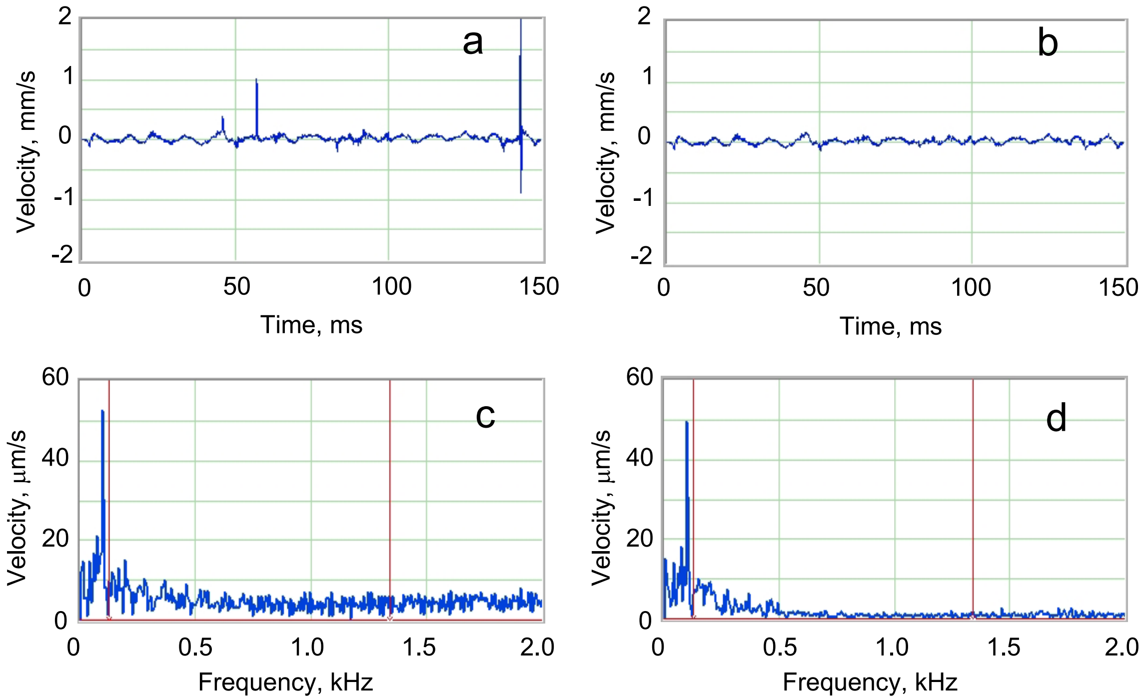

Figure 7. Spike reduction by using the non-linear "spike-removal" filter. (a) and (c) raw time domain velocity signal and a corresponding spectrum; (b) and (d) time domain velocity signal with spikes removed and a corresponding spectrum.

When the spike duration is longer than a vibration cycle, the "de-spiked" data often has gaps. Since the FFT is based on the energy in the entire time window, these gaps result in a reduction of the reported velocity (peak of the FFT) when many spikes are removed.

We also developed and investigated a method of spike reduction based on knowledge of the carrier signal amplitude. This method can be used in the analog I&Q demodulator and the direct digital carrier sampling FM demodulator, since they both preserve the information on the carrier signal amplitude. In the PLL demodulator, the optical amplitude information is lost. This method is based on the fact that the spikes in the demodulated signal are associated with the low amplitude of the carrier signal.

The procedure here is to find the amplitude envelope of the signal, and define a threshold for the velocity data based on this amplitude. In the software, the threshold level is normalized to 1. Any velocity data that has a corresponding signal amplitude above the threshold is unchanged. Any data with the amplitude below the threshold is scaled by multiplying

the velocity data with the normalized amplitude. Since this multiplies the velocity data by a number less than 1, the height of the "spikes" commonly observed at low speckle amplitudes are reduced.
Using the data envelope information, it is possible to significantly improve the noise floor and SNR of the demodulated velocity data. The basic procedure is as follows:

1. A threshold is selected, and the envelope signal A(t) is divided by this value so that a normalized representation of $A_n(t)$ is created.
2. When $A_n(t)$ is above the value 1.0 (the original signal is above the threshold), then the instantaneous velocity v(t) is left unchanged.
3. Otherwise, the normalized value $A_n(t)$ is used as a multiplier to reduce the value of the corresponding v(t). As an alternative, we have also tried using the same algorithm with the *square* of the normalized envelope used as the multiplier, (A_n^2 (t) is used when $A_n(t)$ is less than unity).

With this method, the areas with the largest spikes, which correspond to the regions of the smallest envelope, are affected the most. In addition, a small envelope situation often creates only a phase discontinuity in the velocity data, without an apparent spike. By using the amplitude multiplication, the effects of these discontinuities are also reduced.

Figure 8 shows an example of application of this method to the data set taken with the direct carrier sampling digital FM demodulator shown in Figure 7. The amplitude correction improved the SNR by about 12.5dB.

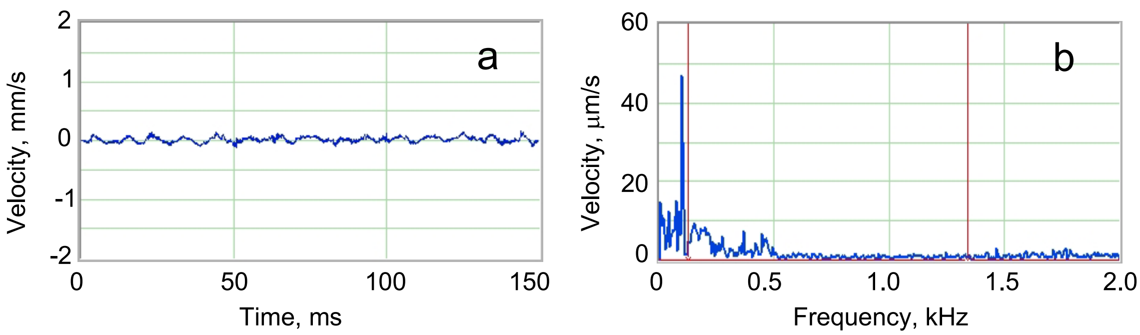

Figure 8. Spike reduction by using the method based on knowledge of the carrier signal amplitude. (a) Time domain velocity signal of the data set shown in Figure 7(a) with spikes removed and (b) a corresponding spectrum.

A third technique based on wavelet transform has also been developed for spike detection. The basic procedure is as follows. The wavelet decomposition of signal s (t) is calculated. The results are wavelet coefficients, or details. The first level detail coefficients are used to detect spikes. They are compared to a threshold. The universal threshold proposed in paper[9] can be used. The threshold subdivides the wavelet coefficient into two sets, the coefficients above the threshold represent spikes. The coefficients below the threshold are set to zero and the coefficients above the threshold are left unchanged. Then the inverse wavelet transform is calculated. The result is in the signal domain and yields a time series of zeros except for the points that are spikes. The positions of the non-zero points identify the locations in the signal where the spikes exist. The spike points are removed from the signal and the gaps are interpolated using the linear or cubic interpolation curves. The method can be used with any demodulator.

The proposed de-spiking procedure for an input signal s(t) involves the steps:
Wavelet domain:

1. Decompose s(t) and get the first level detail coefficients $C_{1,i}$ (User can choose the mother wavelet from a list.)
2. Select a threshold and identify points of spikes where $abs(C_{1,i}) >$ threshold. (User can choose a threshold).
3. Create a temporary array TMP of size $C_{1,i}$ of zeros except for the points of spikes.

Signal Domain

1. Get inverse wavelet transform of TMP. The result is the array SPK(t).
2. Positions of non-zero points in SPK correspond to spikes in the signal s(t).
3. Remove spike points from the signal s(t).
4. Interpolate the gaps. (User can choose linear or cubic interpolation methods).

Figure 9 shows an example of application of the developed wavelet threshold method to a signal of a continuously scanning LDV shown in Figure 7 (a). The speed of laser beam was 4 cm/s. The method improved the SNR by about 10dB.

The wavelet threshold method has been used to reduce spikes in field data taken with the 16 channels continuously scanning MB LDV with the PLL demodulator. Figure 10 shows the noise reduction in the continuously scanning LDV signal as a result of using the wavelet threshold method. The speed of beam was 5cm/s. The noise floor of the velocity signal was reduced by approximately 15 db for both the single tone and the broadband vibration. Figure 11 shows the improvement of the velocity contrast of the velocity images of some buried landmines by applying the wavelet threshold method to the velocity signals.

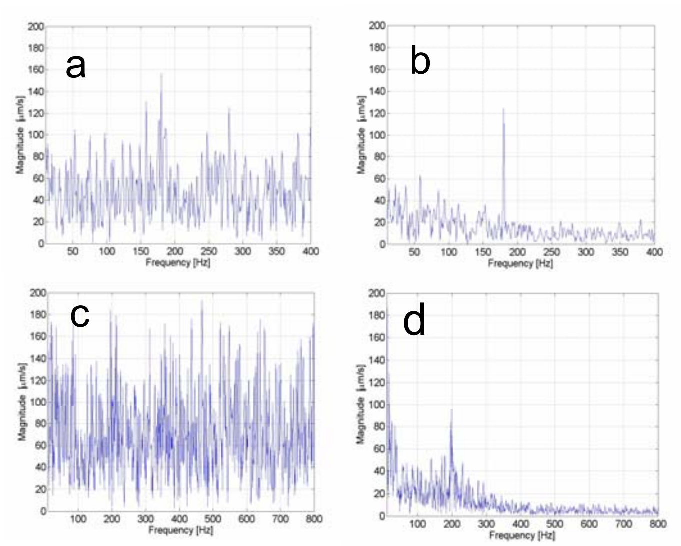

Figure 10. Noise reduction in a continuously scanning LDV signal by removing spikes with wavelet threshold method. Spectrum of a velocity signal taken in the field with the continuously scanning MB LDV. (a)- spectrum of a velocity signal with single tone excitation, F= 180Hz; (b) - the same signal processed with the wavelet threshold method; (c) spectrum of a velocity signal with random noise excitation, (d) – the same signal processed with the wavelet threshold method.

Figure 11 (a) and (b) shows the velocity image of an antitank mine VS 2.2, one inch deep without and with using the wavelet threshold method for spikes reduction. In this example the ground was excited with a very low level single tone vibration to get the ground velocity on the order of speckle noise. Application of the wavelet threshold method reduces the speckle noise and reveals the image of the mine. Figures 11 (c)-(h) show improvement of the velocity images of the mines that were hard to see with a regular excitation level used in field by applying the wavelet threshold method.

CONCLUSIONS

Spikes in the demodulated velocity signal are one of the major sources of noise in a continuously scanning LDV, and are caused by low SNR at the areas of the speckle field with low light amplitude or phase discontinuities. Frequency demodulators with lower threshold and better SNR produce short unidirectional spikes which can be easier detected and removed from the output signal. Several methods of spikes removal from an LDV signal have been developed. The non-linear “spike-removal” filter and the wavelet threshold method can be applied to the velocity signal of any demodulator. The methods using the amplitude information of the carrier signal are applicable to both baseband I&Q demodulation and digital FM demodulation by direct carrier sampling. When each type of correction is applied, experiments show that the amplitude methods, used with the baseband I&Q demodulator and the digital FM demodulator, provide better results than the PLL demodulator. Development of low threshold multi-channel I&Q and digital demodulators, incorporating the developed methods of spike reduction for field data, is a high priority task of the future work.

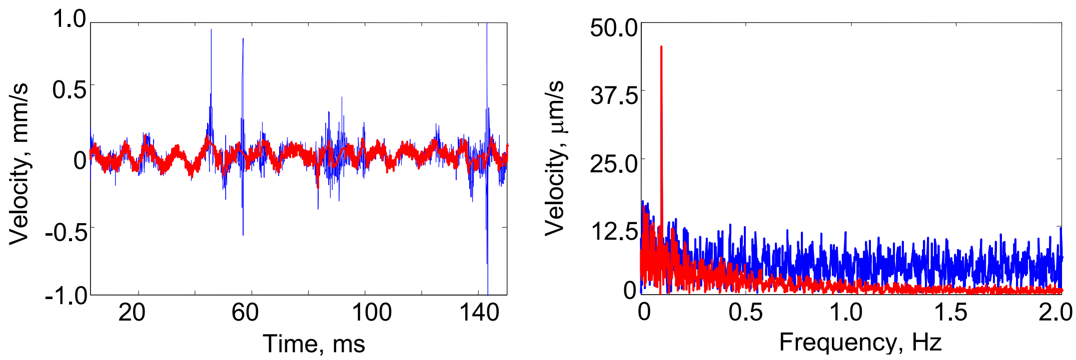

Figure 9. Spike reduction by using the wavelet threshold method. (a) time domain signals and (b)corresponding spectra, of a continuously scanning LDV at the speed of beam 4 cm/s. Blue is for raw signal and red is for the signal processed with the wavelet threshold method.

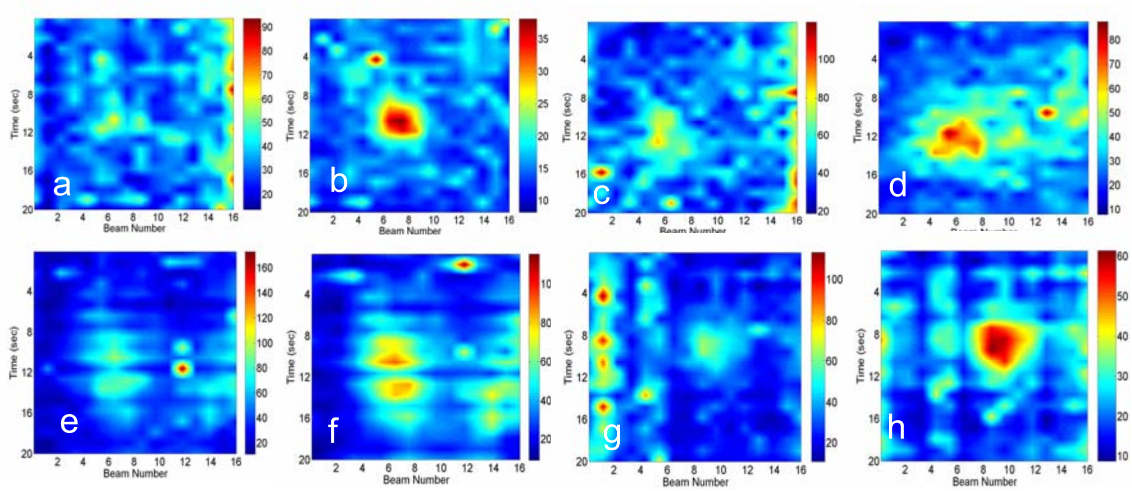

Figure 11. Velocity image of buried antitank mines. (a) Single tone low level excitation, the ground velocity is on the order of value of the velocity noise floor, (b) the same mine after wavelet threshold method was applied; (c) – (h) Random noise excitation, (c) M15, 5 cm deep, before and (d) after the wavelet threshold method was applied; (e) TMA4, 5 cm deep, before and (f) after the wavelet threshold method was applied; (g) VS 1.6, 15 cm deep, before and (h) after the wavelet threshold method was applied.

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